Investigation Report
6DG3 Debut Reflux Pump Failure

Date & Time the Incident Began: 12/1/10 6:20 AM
Investigation Start Date & Time: 12/13/10
Report Date: 1/20/11
Investigation Team Members: Scott Johnston, Matt Shores

Incident Summary:
On 12/1/10 at the CRU1 Spare Debutanizer Reflux Pump, 6DG3A, experienced a seal failure that led to an atmospheric butane release of 4300 lbs between 6:22 to 8:08 AM. This incident is classified as: API; D2 – Actual, C4 – Potential (People) and Process Safety Incident.

As a result of the pump failure CRU1 was brought down due to the main Debutanizer Reflux pump being out of service from steam turbine driver repairs. An emergency work order was generated to replace the mechanical seal on 6DG3A. CRU1 was back up and operational a day later on 12/2/10.

Problem statement:

Expected: Design and operation of single seals with disaster bushings prevent large releases in the event of a seal failure.

Actual: On 12/1/10, 6DG3A seal leaked 4300 lb butane and propane to atmosphere.

Impact: CRU#1 shutdown.

Note this investigation is evaluating exclusively the cause of the pump seal failure and excluding the Operation and emergency response actions taken as recovery measures.

Situation Description:

On December 1, 2010, the CRU#1 Lead Outside Operator was doing his start of shift rounds and discovered 6DG3A debut reflux pump iced-up and blowing product to the atmosphere. He contacted the Console Operator to initiate an emergency shutdown of CRU#1 and evacuated the unit of all non-essential person (level 1). Outside operators aimed 3 stationary monitors and a Stang monitor at the pump. 5th street from Best street to D street was closed. The outside operator opened the debut overhead drum to depressure the debut system. At around 7am, the pump was isolated using 6AOV3 (DP70 valve) on the suction line.

Pump History:

Both CRU1 Spare Debutanizer Reflux Pumps (6DG3, 6DG3A) have a history of seal failures at an average frequency of one failure per year. The two pumps, while of different make and models, both have a history of running below the OEM minimum stable continuous flow of 400 BPH @ 3600 rpm. The average flow rate in the months leading up to this specific failure was 200-350 BPH. Due to difference in impeller designs the low flow rate (below OEM minimum stable continuous flow) more adversely impacted 6DG3A than 6DG3 causing high suction recirculation, increased vibration levels, and higher pumping temperature.

Both pumps had been identified as bad actors and were discussed at the monthly MEI/Flowserve Bad Actor meetings. In 2007 a recommendation and request was submitted to install an unpressurized API plan 52 dual seal system installed on both pumps. For the 6DG3A pump, the installation of the dual seal was pending a tie-in location in the flare line. Nonetheless, 6DG3A had an API RV9 upgrade (pull-out, thicker shaft, increase space for dual seal, more robust bearings,) installed in March 2010 but with a single seal in dual seal gland, which failed on LDAR in May.

By July 2010, the seal design was changed from single seal in a tandem gland to a QBQ with close-clearance floating throat bushing. This change also included an API plan 62 water quench to eliminate previous seal failures due to collection of solids on the seal faces. The new water quench required the mechanical seal gland drain plug to be removed to prevent the water from accumulating.

Table 1 - 6DG3 vs. 6DG3A Pump Comparison

	6DG3	6DG3A
Manufacturer:	United	Ingersoll Rand
Model:	4" TC-A (top in, top out)	3x4x10A (side in, top out)
SN:	74793	058020
Diameter:	8-3/16"	8.88"
Nss	12,757	15,050
Duty at BEP:	800 gpm @ 225 TDF	400 gpm @ 275 TDF
Normal Flow Rate	200 – 400 BPH (140-280 gpm)	200 – 400 BPH (140-280 gpm)
% BEP Flow (normal):	17.5% to 35%	35% to 70%
Min Stable Continuous Flow (per OEM):	300 gpm/420BPH (37.5% of BEP)	280 gpm/400 BPH (70% BEP)
NPSHR @ normal flow rate: NPSHA per data sheet (8 ft)	3-4 ft	7-8 ft

Sequence of Events:

Sequences of Events on 12/1/10. Resources include Interviews, Radio Logs, and Historized Process Data.

Time (AM)	12/1/10 Event Description
5:00	Nightshift lead outside Operator performed round, no sign of leak
5:30 to 6:00	Shift Turn-over
6:15	Lead outside operator (LOO) performs bump test of gas testers
6:22	Pump seal leak started
6:30	LOO left operator shelter to start rounds, noticed apparent steam leak over pump row
6:43	LOO called to notify CO and OO about leak and CRU1 shutdown
6:44	LOO put steam hose and leak and began to cut charge
6:48	Advised to contact STL and blow unit Horn
6:48 to 6:50	Started three fire monitors to knock down cloud
6:50	Outside operator trips 6DGT3A turbine
6:51	LOO trips CRU1 charge pump (FC21)
6:51	STL notified ER of leak and shutdown
6:55	Outside Operator opens E-dump outside valve on Debut Accum Drum
6:59	Shutdown 6DG24 absorber bottoms Debut feed pump
7:03	Debut feed shutdown (6FC25)
7:03	LOO closed AOV3
7:29	6DG24 pump slow rolled to flush coil
7:45	Debut system reached 30 psig
8:08	6DG3A pump blocked in
8:12	STL notified that OK to open road
8:23	BOHO worried about fire water pressure, monitors already turned off
8:23	6DG24 pump blocked in

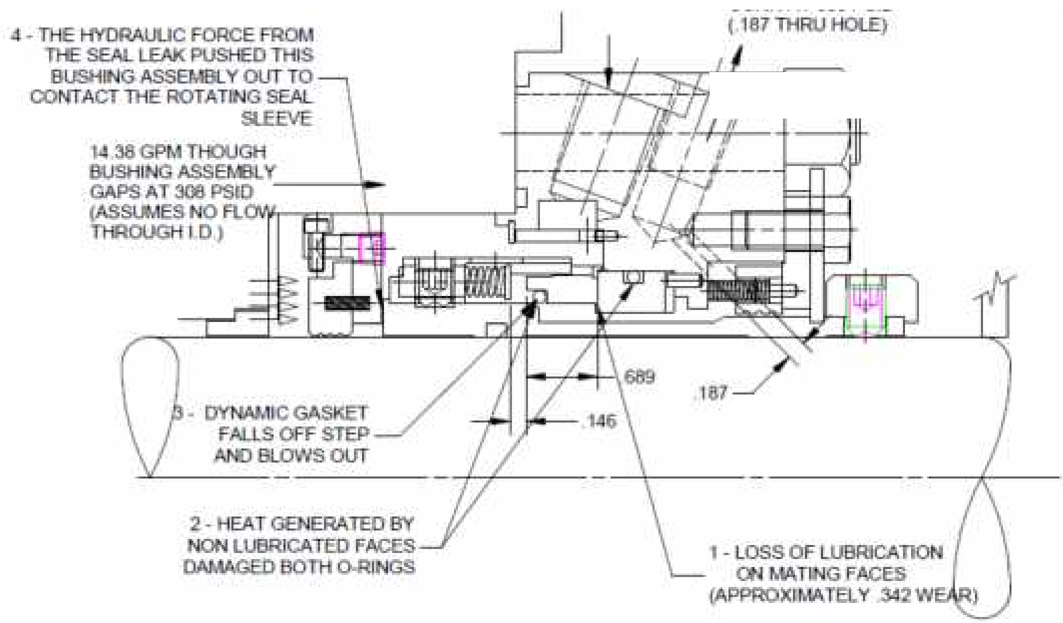
Cause Analysis:

As noted in the history timeline, it is estimated that this pump (6DG3A) had approximately 2 weeks of run time leading up to the seal failure and during that time the seal faces ran completely or mostly dry. This caused the seal faces to wear such that the face magnitude of wear was greater than the travel for the rotating face gasket (aka, dynamic gasket or oring) causing the gasket to fall off the seal sleeve land (refer to figure 1). Once that happened, the mechanical seal faces were bypassed and a new atmospheric leak path was introduced. Note that the new differential pressure was great enough to move the close-clearance throat bushing into the back side of the rotating sleeve, causing galling.

Seal Water Quench Drain

The new seal design implemented an API plan 62 water quench to eliminate previous seal failures due to collection of solids on the seal faces. The new water quench required the mechanical seal gland drain plug to be removed to prevent the water from accumulating. The open seal gland drain plug now created a new leak path in the event of a seal failure. The open drain plug reduced the effectiveness of the installed pump seal disaster bushing.

Figure 1 Seal Drawing with Sequence of Events Leading up to Failure

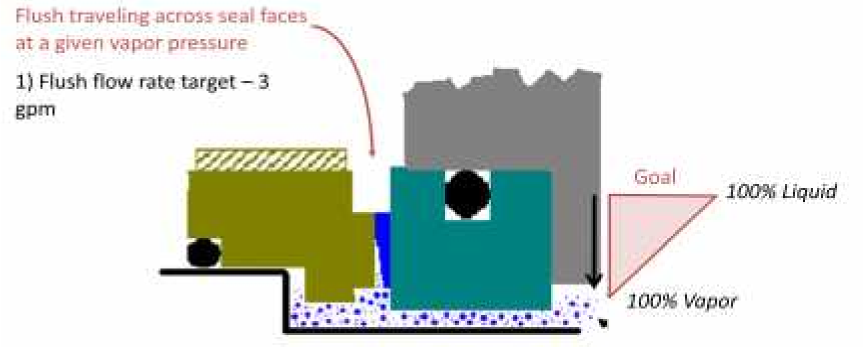


Seal Face Wear Contributing Causes

Pump Seal Flush Design

Seal flush flow volume is critical to pump seal life as it removes heat, lubricates the seal faces, and increase the vapor margin (pressure) in the seal cavity thereby ensuring a lubricating environment for the mechanical seal faces. The goal is to have the liquid flush on the seal side gradually turn into vapor as it crosses the seal faces, such that there is less than 500 ppm vapor on the atmospheric side. A rule of thumb for selecting seal flush flow is 3.0 gpm and 25 psi vapor pressure margin or 30% above the vapor pressure, whichever is highest.

Figure 2 Seal Flush Operation/Design



Why did the 6DG3A seal faces run dry from 11/15-12/1/10?

There were several conditions that the pump seal was subjected to in order to cause complete vaporization across the seal faces:

1. By design, 6DG3A seal chamber vapor pressure was marginal (nearly at fluid vapor pressure).
   AND
2. For the entire run period, 6DG3A was internally recirculating (pump operation continuously below minimum flow).
   AND
3. Since March 2010, the temperature at the seal faces increased a sufficient amount (RVX upgrade).
   AND
4. Since July 2010, the flush flow rate decreased a sufficient amount (close-clearance throat bushing seal upgrade).

These are explained in more detail below.

1. **By design, 6DG3A seal chamber vapor pressure was marginal (nearly at fluid vapor pressure).**

   The product was butane, which has relatively high vapor pressure. The pump discharge pressure was low relative to the vapor pressure, so the vapor pressure margin within the seal was small by design. Specifically:

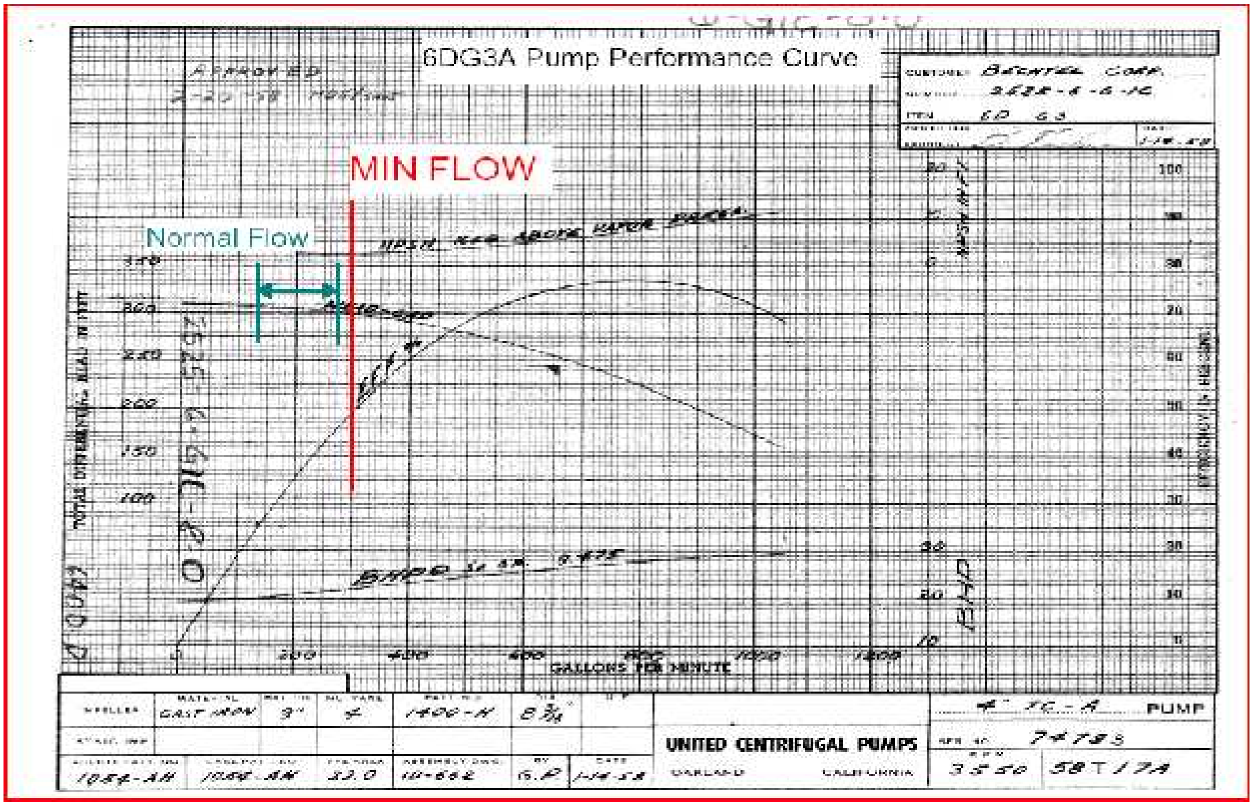
   > The pump suction vapor pressure can be assumed to be the same pressure as the debut OVHD accumulator (6PC106B). The pump suction pressure is approximately 30 psia higher than the vapor pressure. However, the vapor pressure in the seal chamber is higher due to the increased temperature caused by pump cavitation. The 6DG3A pump NPSHA and NPHR are both around 8 ft. The NPSH margin (available over required) is around 0 ft, much lower than the preferred 3 ft margin. Having no NPSH margin indicates that the pump always operating between incipient to full cavitation. It is estimated that the seal chamber temperature is a 5-10 F higher than the pump suction temperature. The higher temperature decreases the vapor pressure margin at the seal faces. The estimated vapor pressure margin at the seal faces is less than 10 psid (versus 25 psi recommended).

2. **Pump Operation Continuously Below Minimum Flow**

   The two pumps while of different make and models both have a history of running 95% of the time below the minimum continuous flow of 400 BPH (@ 3600 rpm). The average flow rate in the months leading up to this specific failure was 200-350 BPH. Due to difference in impeller designs the low flow rate (below minimum flow) more adversely impacted 6DG3A than 6DG3 causing high suction recirculation, increased vibration levels, and higher pumping temperature.

Low flow recirculation increases discharge temperature and therefore seal flush temperature. Higher temperatures of this fluid reduce the vapor pressure, thereby reducing the seal cavity vapor pressure margin even smaller.

Figure 3 6DG3A Pump Performance Curve and Normal Operation



3. RVX Upgrade

In March 2010, PSR installed an RVX upgrade on this pump, which is a bigger shaft requiring bigger diameter seal faces. This resulted in increased heat generated by the seal faces, which means increased (hotter) vapor pressure and a decrease in the vapor pressure margin. The pump seal flush orifice was 0.136”.

4. Close-Clearance Throat Bushing Design Upgrade

In July 2010, the seal design was changed from single seal in a tandem gland to a QBQ with close-clearance floating throat bushing. This bushing increases seal chamber pressure, which reduces the amount of flush flow. Accordingly, a new seal flush orifice size was calculated (0.172”) and was put on the new seal drawing, but the Plan 11 flush orifice size was left the same (0.136”) in the field. Note that the seal OEM recommended removing the seal flush orifice all together to get an ideal seal flush flow of 3.0 gpm after the incident.

Why did we leave the flush orifice the same size during the July repair (0.136 since 2008)?

1. The machinists left the orifice the same during the July repair.
   AND
2. The Mechanical Specialist approved the July installation with the same orifice.

   Note that the way work is done at PSR, the machinists do the work and the Mechanical Specialist approved the work since he was the Responsible Party for the change.

1. Why did the machinists leave the orifice the same during the July repair?

The machinists thought the job scope was solely the new seal and water quench (API 11 stayed the same). The job scope was communicated verbally, focusing on the quench and seal and Verbal communication of scope was an established practice (no package written). The only location indicating the orifice size was on the seal drawing, which was:

- used for orientation, to verify all parts present and the type of flush plan.
- viewed as complex and difficult to read (e.g., font).
- stand-alone (no revs, no indication of change).

In addition, the machinists assumed any other changes that needed to be made would be pointed out by the Mechanical Specialist. They saw the Mechanical Specialist was managing the change on this pump and assumed the Mechanical Specialist was using Flowserve's expertise. It was established practice to follow MEI direction for pump repair plans and upgrades.

2. Why did the Mechanical Specialists approve the July installation with the same orifice?

The Mechanical Specialist thought the job scope was solely seal and water quench (Plan 11 stayed the same) and that was what the machinists installed.

The Mechanical Specialist assumed the orifice was acceptable as it was, because he knew that Flowserve reviewed the change and also, he assumed that if the flush plan stayed the same, the orifice would as well.

The Mechanical Specialist thought his review of the orifice install was complete if it was installed and stamped.

Why did the Mechanical Specialist think the job scope was solely seal and water quench?

Flowserve verbally told the Mechanical Specialist the scope was seal change and water quench (no mention of orifice/throat bushing) and informed him of the scope via the MOC initiation & failure analysis report (no mention of orifice/throat bushing). The Mechanical Specialists, in turn, expected Flowserve to communicate any other needed changes in person or in email.

Flowserve chose to communicate the orifice size on the seal drawing only and assumed Shell would see the new orifice size on the seal drawing when they went to install as they considered Shell machinists to be thorough.

Shell viewed Flowserve as responsible for the entirety of any change/recommendation we believed our fixed-fee agreement with Flowserve guaranteed this. They were the OEM (have the design resources) and we consider them as the seal experts. It was an established practice for Flowserve to communicate in person or email as they were located just down the hall.

Observations, Insights, and Conclusions:

1. Pump Operational Continuously Below Minimum Flow	
Observation	The CRU1 Debutanizer Reflux pumps, 6DG3/3A, have a history of operating below minimum flow (400 BPH @ 3600 rpm) to maintain energy efficiency of the column. Pump operation in this region increases the probability of pump/seal failures.
Insight	Either running the column efficiently was more highly valued or Production was unaware of the consequences of running this pump below minimum flow.
Conclusion	There are likely other pumps running below minimum flow in competition with other operating needs and they will continue to result frequent failures.

2. Communicating Scope of Work	
Observation	Flowserve “provides descriptive email of change and answers any questions” Shell expects Flowserve to bring any/all “changes to my attention” Description of G3A change was seal and quench only. Orifice size for flush was noted on seal drawing (but not noted as a change).
Insight	It’s likely that Flowserve assumed Specialist/Machinist would notice the orifice size and make the change, but Shell folks assumed Flowserve would verbally tell them or email them about changes like that. These assumptions left a gap in understanding & completion of the work scope.
Conclusion	We (Shell) may have been relying so heavily on Flowserve, that we stopped making sure the work scope is understood and installed correctly for ourselves.

Recommendations:

1. Pump Operation Continuously Below Minimum Flow	
What cause should be addressed?	6DG3A was internally recirculating for the entire run period.
Why? What would be the benefit?	Recirculation caused by running below minimum flow for both debut reflux pumps was not only a contributing cause to this incident but has created a long history of low reliability.
How? What would be the solution?	Address the design of the 6DG3/3A pumps, which are way oversized for the service, by either slowing them down or replacing the impeller with something that would achieve both the operations needs for tower efficiency and minimum flow for the pump.
How the solution would have prevented the incident	Recirculation was a contributing factor to the reduced vapor pressure margin. It is unlikely that addressing this by itself would have prevented the issue (see recommendation #2).
Action Plan:	**Who:** Matt Shores **Action:** Adjust operation of both 6DG3 and 6DG3A pumps to move normal operating values to above minimum flow be reducing the normal operating speed to 2850 rpm. Minimum flow of 315 BPH @ 2850 rpm. **When:** <u>Complete</u> per M2011225-001 **Who:** Matt Shores **Action:** Implement pumps low flow target alarm of 315 BPH. **When:** <u>Complete</u> on same day as MOC M2011225-001 **Who:** Matt Shores **Action:** Evaluate ability to re-rate 6DG3 to improve pump efficiency. **When:** <u>Complete</u>. Given pump case design and NPSHA constraints there is not an available pump re-rate. **Who:** Matt Shores **Action:** Evaluate ability to re-rate 6DG3A to improve pump efficiency. **When:** <u>Complete</u>. Pump can be re-rated with new impeller and pump case modifications. Re-rate would allow pump to run closer to BEP at 315 BPH than existing pump hydraulics. **Who:** Matt Shores **Action:** Evaluate need for minimum flow recirculation line. **When:** <u>Complete</u>. Min flow recirculation line will allow pump reliability to by running closer to BEP, but not required to run above minimum flow (315 BPH @ 2850 rpm).

2. Pump Seal Lubrication Design (Vapor Pressure and flush flow)	
What cause should be addressed?	By design, 6DG3A seal chamber vapor pressure was marginal (nearly at fluid vapor pressure).
Why? What would be the benefit?	The process design conditions (process fluid and differential head) for this pump is significantly marginal for reliable seal lubrication. All the changes made to this seal over time have been attempting to cope with the resulting seal failures including the change in July 2010, where the installed pump seal flush orifice size was smaller than necessary to provide adequate pump seal flush flow.
How? What would be the solution?	Change to a seal design that is no longer dependent on the process fluid to provide lubrication to the seal faces.
How the solution would have prevented the incident?	The installation of the Plan 53 in March 2010 would have moved the seal lubrication from the seal chamber process fluid to a pressurized barrier fluid provided by a seal pot. The barrier fluid vapor pressure margin is sufficiently large and easier to control. Indeed, the operation of the seal would have been that there would have been no LDAR failure or need for installation of a different seal and flush orifice in July. Note that if there had been a leak, the hydrocarbon what came out of the seal would have been routed to the flare, so the impact of any leak would have been significantly reduced.
Action Plan:	**Who:** Matt Shores **What:** For interim mitigation, ensure the current seal flush orifice sizes that are installed are correct for both 6DG3 and 6DG3A, modify as needed and ensure they are not plugged. **When:** <u>Complete</u>. **Who:** Jim Walker **What:** Complete installation of API Plan 53B on 6DG3A and ensure this pump is used as a primary pump. **When:** 5/30/12

3. Communication of Changes to Pump Seals	
What cause should be addressed?	We left the flush orifice the same size during the July repair (0.136 since 2008).
Why? What would be the benefit?	As we work to improve our seal reliability, seal changes and upgrades happen frequently. Flush orifice sizes are a critical factor in healthy seal operation and are likely to change with any seal design change. Comments from MEI suggest that these changes are happening more frequently than they did several years ago. Another benefit would be improving overall change communication to the machinists in the field, thus preventing other critical design factors from being missed.
How? What would be the solution?	1. Update repair sheets to include orifice information. 2. Educate machinists and technical support staff on the impact flush orifice size has on seal operation and why paperwork will change. 3. Change the way we accept changes from Flowserve and communicate them to the machinists. This includes: a. Flowserve providing a finalized seal drawing, which is reviewed and approved before work is continued. b. MEI providing a written scope of change to the machinists; the form could be akin to a range change form and includes orifice size, flush lines, throat bushing, materials, etc).
How the solution would have prevented the incident	1 & 2 – Learning about this particular failure mechanism (the orifice size being specific to the seal design) would have prevented the assumption that there is a "standard" orifice size or that only cleaning of the orifice would be required. Additionally, the machinists may have asked about the flush orifice size, when, as they were filling out the repair report, they recognized a discrepancy between field and drawing. 3 – In this incident, the scope of work which was evaluated by MOC and executed in the field was the "concept design" proposed by Flowserve. By requiring a final design version before MOC or work in the field is completed, the design package would have included the final orifice size. A written package may have highlighted this change, as well.
Action Plan:	**Who:** Renee Majumdar **What:** Conduct a Learning Session with all personnel in Machinery discipline and Flowserve. **When:** Complete **Who:** Matt Shores **What:** Added pump repair sheet item to verify that the pump seal drawing orifice diameter matches the orifice diameter installed in the field **When:** Complete

	Who: Jaylynn Jackson **What:** Validate flush orifice size calculation process. **When:** 7/2/12 **Who:** Jaylynn Jackson **What:** Develop assurance process to where machinists have been provided a written plan for seal/seal plan changes with correct drawing prior to beginning work on machinery changes. **When:** 7/2/12 **Who:** Jaylynn Jackson **What:** Develop and execute process for MEI to review and approve any seal or seal plan drawings prior to work continuing (MOC approval or in machine shop). **When:** 7/2/12 **Who:** Michael Burke **What:** Modify procedures at Machine Shop that when executing seal and seal plan changes (where an MOC is used), written specifics will be required before beginning re-build work (that is, after tear down and inspection). **When:** 9/2/12 **Who:** Matt Shores **What:** Conduct audit effectiveness of approved corrective action (for 6DG3A Seal Leak Investigation) made in MEI-Flowserve-Machinist work process and report back to Engineering Manager (over both MEI and Machinists). **When:** 4/2/13

4. Seal Water Quench Drain	
What cause should be addressed?	Since 7/30/10, 6DG3A seal had an open drain on the atmospheric side.
Why? What would be the benefit?	Pump seal design had water quench on atmospheric side of seal to reduce seal failures due to solids accumulation on atmospheric side of seal. Design requires open drain to prevent flooding of atmospheric section of pump seal gland. Open drain bypasses disaster bushing.
How? What would be the solution?	Reduce drain area that bypasses the disaster bushing by installing a restriction orifice.
How the solution would have prevented the incident	It would have reduced the amount of hydrocarbon that was escaping through the seal and water drain, but not have prevented the seal failure.

Action Plan:	**Who:** Matt Shores **What:** Update API plan 62 water quench standard drawing to include a note regarding potential issues to consider when opening the drain line. **When:** Complete **Who:** Jaylynn Jackson **What:** Conduct a survey for any disaster bushings with open drains from quench in all services. Develop recommendations for mitigation, if any. Open additional Fountain action items as necessary. **When:** 4/5/12 **Who:** Jaylynn Jackson **What:** Validate if an API Plan 62 could be used in light hydrocarbon services. **When:** 4/5/12

Attachment 1: Cause Tree

6DG3A Cause tree.vsd

Attachment 2: Timeline

timeline.vsd

Attachment 3: CRU1 Debutanizer Reflux Pumps History

Prior to 2005 both 6DG3 and 6DG3A average about 1 repair per year according to repair reports dating back to 1990. The years 2005 to 2010 are covered more extensively in the table before. Refer to the color decoder ring below to identify the recorded event with its subsequent category.

6DG3A Pump Events
6DG3 Pump Events
6DGT3A Turbine Events
6DG3A Modifications
Unit/Other

Year	Date	Description
2005	12/9/05	Pump Repair – LDAR Failure
2006	8/31/06	Pump Repair – LDAR Failure (WO 6000406453)
	9/06	Changed from John Crane seal to Flowserve Seal

		Both 6DG3/3A are on the Phase I list for Pump Safety Project. Neither pump made the final cut to be upgraded.
2007	8/07	Pump RVX and dual seal for 6DG3A quoted and recommended to Operations as upgrades
	11/2/07	Pump Repair – LDAR Failure (6000426402)
2008	4/8/08	Pump Repair- LDAR Failure (WO 6000576734)
		6DG3A RVX and dual seal upgrades ordered, un-successfully attempted to expedite installation on April failure.
		6DG3A – Installed larger seal flush orifice after April failure per recommendation from 0.090" dia to 0.136" dia.
	7/28/08	Pump Repair – Seal Leak, LDAR (WO 6000612363)
	11/08	6DG3A Dual Seal auxiliary system Engineering BOM (9873) issued
2009	2/3/09	Pump repair (bearing failure) – (WO 6000669142)
	7/31/09	Pump Repair – Seal Leak – LDAR WO 6000717134
	12/1/09	Pump Repair – Seal Leak – LDAR – WO 6000514428
2010	3/4/10	6DG3A Pump RVX upgrade installed with single seal in dual seal gland; M2010629-001
	4/19/10	RVX Upgrade Ordered for 6DG3
	4/1 to 5/1	Pumps down for unit regen
	5/10/10	Pump LDAR Failure – WO 6000803801
	5/29/10	Tandem Seal Notification Written
	6/19/10	6DF2 Heater Fire – CRU1 SD
	6/19 to 7/24	CRU1 Unit mostly SD – running on 6DG3 pump
	6/10	2011TA Addendum Item submitted to modify flare line to allow tie-in connection for API plan 52 dual seals.
	7/13/10	Decision made to send Dumbo gas to FCCU when possible
	7/30/10	Installed new seal design with water quench WO 6000817396 – MOC M2010655-001
	7/30/10	6DGT3A put on emergency use only due to excessive vibration
	10/12/10	Pump offline – successful LDAR monitoring of 37 ppm
	10/26/10	6DGT3A Turbine repairs complete, returned to service
	11/12/10	Pump offline – successful LDAR monitoring of 12 ppm
	11/15/10	6DGT3 – Main pump turbine pulled for hydraulic governor upgrade
	11/15/10	6DG3A – Pump started since time since turbine repair
	12/1/10	6DG3A - Catastrophic seal failure – WO 6000860678 **Pump ran for approximately 15-16 days**
	12/1/10	Unit SD due to 6DG3A pump failure and 6DG3 turbine OOS
	12/2/10	6DG3A New seal design installed without the water quench – MOC M20101195-001
	12/2/10	6DG3A Pump turned to service and pump/unit started back up
	12/16/10	6DGT3 Turbine returned to service
	12/16/10	6DG3 Pump started after turbine was returned to service